Have Atmospheric Čerenkov Telescopes Observed Dark Matter?

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Abstract

Two ground-based experiments have recently independently detected TeV γ-rays from the direction of the Galactic center. The observations made by the VERITAS and CANGAROO collaborations are unexpected, although not impossible to interpret in terms of astrophysical sources. Here we examine in detail whether the observed γ-rays may arise from the more exotic alternative of annihilations of dark matter particles clustered in the center of the Galaxy.

1   Introduction

Recently, the VERITAS [1] and CANGAROO [2] collaborations, using the Whipple 10 meter and CANGAROO-II Atmospheric Čerenkov Telescopes (ACTs), respectively, have made significant detections of TeV γ-rays from the Galactic center region. Although the origin of this emission is not yet known, there are several possible, although unlikely, astrophysical sources in the field of view. Alternatively, this may be a signature of annihilating dark matter particles.

The Galactic center is a complex and rich region. Its most notable inhabitant is a $2.6 \times 10^6 M_\odot$ black hole, coincident with the radio source Sgr A*, which also demonstrates variable emission at infra-red [3], soft X-ray [4] and hard X-ray [5] wavelengths. Additionally, the region may contain massive X-ray binaries emitting relativistic plasma jets (microquasars) capable of producing high-energy γ-rays [6] by either hadronic (π^0 production) [7] or leptonic (inverse Compton) [8] processes. The region could also contain Supernova Remnants (SNRs) which are widely believed to be the source of Galactic cosmic rays. TeV γ-rays have indeed been observed from several nearby supernova remnants such as the Crab [9] and Cas A [10]. The responsible mechanism remains unclear, but again could be either leptonic or hadronic (see Ref. [11] for a discussion of TeV γ-ray production in SNRs). The SNR Sgr A East lies only a few parsecs away from Sgr A*, but is not a likely TeV source in itself [12]. Interactions of its expanding shell with molecular clouds in its environment could, in principle, produce high-energy γ-rays [13].

Alternatively, strong winds from massive O and B type stars could lead to hadronic interactions that may result in the emission of high-energy γ-rays [14, 15]. Two massive, compact, young star clusters which contain such stars (Arches and Quintuplet) are located roughly 10 arcminutes away from the Galactic center. Chandra observations of the Arches cluster have revealed non-thermal emission attributed to relativistic electrons accelerated in colliding wind shocks from binary systems within the cluster or in the winds from single stars with the collective winds from the other stars in the cluster [16, 17]. It is argued that the existence of non-thermal particles could result in X-ray/γ-ray emission by inverse Compton scattering of ambient photons.

Observations by INTEGRAL [18] and EGRET [19] have revealed γ-ray emission from the Galactic center region, although thus far no corresponding sources have been identified. X-ray surveys of the region have revealed a new population of discrete sources, many of which resemble X-ray binaries (see Ref. [20] and references therein). For more information on the Galactic center region, see Refs. [20, 21, 22].

Despite the extensive body of evidence in favor of cold, non-baryonic, dark matter [23], its identity remains elusive. Searches for particle dark matter have been carried out using a variety of methods. Direct searches attempt to observe the recoil energy as Galactic dark matter particles orbiting through the Solar system scatter elastically off nuclear targets [24]. Indirect searches attempt to observe the products of dark matter annihilations such as neutrinos [25], positrons [26], anti-protons [27] and, in particular, high-energy γ-rays [28, 29, 30].

The remainder of this article is organized as follows. In section 2, we summarize the obser-

vations of high-energy γ-ray emission from the Galactic Center region. In sections 3, 4 and 5, we discuss the spectral and spatial features of these observations and assess whether annihilating dark matter could be responsible for these observations. In section 6, we consider particle dark matter candidates suggested by new physics beyond the Standard Model, in particular supersymmetry, in the light of these recent observations. We present our conclusions in section 7. In Refs. [1] and [2], this possibility was briefly discussed. Our intention here is to explore this scenario in considerably more detail.

2   Space and Ground Based Gamma-Ray Observations

Gamma-ray observations of the Galactic Center region have been made in several energy ranges employing a wide variety of experimental techniques. Thus far, space-based γ-ray astronomy has been limited to energies below 30 GeV, mainly due to the fall-off of the photon flux at higher energies given the limited collecting area of satellite detectors. EGRET, the Energetic Gamma-Ray Experiment Telescope [31], launched on board the Compton Gamma-Ray Observatory in 1991, accumulated an integrated exposure of $2 \times 10^9 \, \mathrm{cm^2 \, s}$ towards the Galactic center region. Although EGRET was sensitive in the energy range of ~ 30 MeV $- 30$ GeV, the backgrounds are large and the angular resolution rather poor below about 1 GeV. EGRET detected a strong source of GeV γ-rays in the Galactic center region, although this source appears to be about 10 arcminutes away from the dynamical center of the Galaxy (Sgr A*) [19]. Only an upper limit could be placed on the γ-ray flux from Sgr A* itself. EGRET's successor, GLAST (the Gamma-ray Large Area Space Telescope), is planned for launch in 2006. GLAST will provide a sensitivity of about 50 times that of EGRET (above 100 MeV), a factor of ~ 5 increase in effective area, better angular resolution (less than 0.1° above 10 GeV), and will be sensitive to far higher energies (~ 300 GeV) with an energy resolution better than 15% even at the high-energy end [32].

In addition to satellite-based experiments, ground-based ACTs provide measurements from ~ 200 GeV up to ~ 10 TeV. Typical characteristics for current ACTs are effective areas of $\sim 10^5$ m^2 (dependent on the zenith angle), peak response energies down to a few hundred GeV (dependent on both the zenith angle of the source and its energy spectrum), fields-of-view of a few degrees, angular resolutions of 0.1° to 0.2° and sensitivities down to a few hundredths of the Crab Nebula's flux. The detection technique relies on using the Earth's atmosphere as a calorimeter. One of the components of extensive air showers triggered by γ-rays and cosmic-rays in the atmosphere is Čerenkov radiation produced by the charged component of the shower. Differences in the longitudinal and transverse development between γ-ray and cosmic-ray induced showers are reflected in the Čerenkov images recorded by a high resolution camera located on the focal plane of a reflector (see, for example, Ref. [33]). These differences enable rejection of over 99% of the 'unwanted' cosmic-ray events (see, for example, [34]). In the remaining images, the energy and arrival direction of the primary γ-ray can be deduced.

Detections of the Galactic center at very high energies have been reported by two ACTs

in the past few weeks. The VERITAS collaboration has made observations with the Whipple 10 m telescope [35] on Mt. Hopkins, Arizona. Due to its northern location (31° 57.6' N), these observations had to be made at high zenith angle, resulting in a rather high energy threshold of $\sim 2.8\,\mathrm{TeV}$. Between 1995 and 2003, 26 hours of data were accumulated from this direction, resulting in a 3.7 σ signal with an integral flux of [1]

$$F_\gamma(> 2.8 \text{ TeV}) = 1.6 \pm 0.5 \text{ (stat)} \pm 0.3 \text{ (syst)} \times 10^{-8} \text{ photons m}^{-2} \text{ s}^{-1}. \tag{1}$$

This corresponds to $\sim 40\%$ of the Crab Nebula flux (the 'standard candle' in TeV γ-ray astronomy) above the same energy.

For ACTs located in the southern hemisphere, the energy threshold in the direction of the Galactic center is an order of magnitude lower than that of Whipple. Observations taken during 2001 and 2002 with CANGAROO-II [36] have yielded a $\sim 10\sigma$ detection of the Galactic Center region above ~ 250 GeV [2], with an integrated flux of

$$F_\gamma(> 250 \text{ GeV}) \simeq 2 \times 10^{-6} \text{ photons m}^{-2} \text{ s}^{-1}. \tag{2}$$

These measurements indicate a very soft spectrum ($\propto E^{-4.6\pm0.5}$) and a flux at 1 TeV corresponding to 10% of the Crab Nebula flux.

3 Annihilating Dark Matter: Spectral Characteristics

The annihilations of dark matter particles can produce γ-rays in several ways. First, a continuum of γ-rays results from the hadronization and decay of π^0's generated in the cascading of annihilation products. Second, monoenergetic γ-ray lines are produced as dark matter particles annihilate via the modes $XX \to \gamma\gamma$ and $XX \to \gamma Z$. However the Feynmann diagrams for line-producing processes typically involve loops and thus yield much smaller fluxes than continuum emission. The spectrum of γ-rays from continuum emission depends on which annihilation modes dominate. Annihilations to light quark pairs result in a fairly hard spectrum, while the spectrum is somewhat softer for heavy quarks (*i.e.* $t\bar{t}$, $b\bar{b}$). Annihilations to gauge bosons demonstrates behavior in between these cases. In the energy range above $\sim 10^{-2}$ times the dark matter particle mass, M_X, these variations are mild. At lower energies, the γ-ray spectrum from gauge boson modes flattens (see Fig. 1).

For dark matter annihilations to gauge boson pairs, the resulting γ-ray spectrum can be parameterized as (see Refs. [29, 30])

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \simeq \frac{0.73}{M_X} \frac{\mathrm{e}^{-7.76E_\gamma/M_X}}{(E_\gamma/M_X)^{1.5} + 0.00014}. \tag{3}$$

In Fig. 1, this parameterization is compared to the spectrum obtained using the PYTHIA fragmentation Monte Carlo [37] as implemented in the DarkSusy programme [38].[1] The parameterization of Eq. 3 is reasonably accurate for particles with masses in the range we will be concerned

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[1]Similar results are obtained using the HERWIG fragmentation Monte Carlo [39], as well as by direct evolution of the fragmentation functions measured at LEP using the DGLAP equations [40].
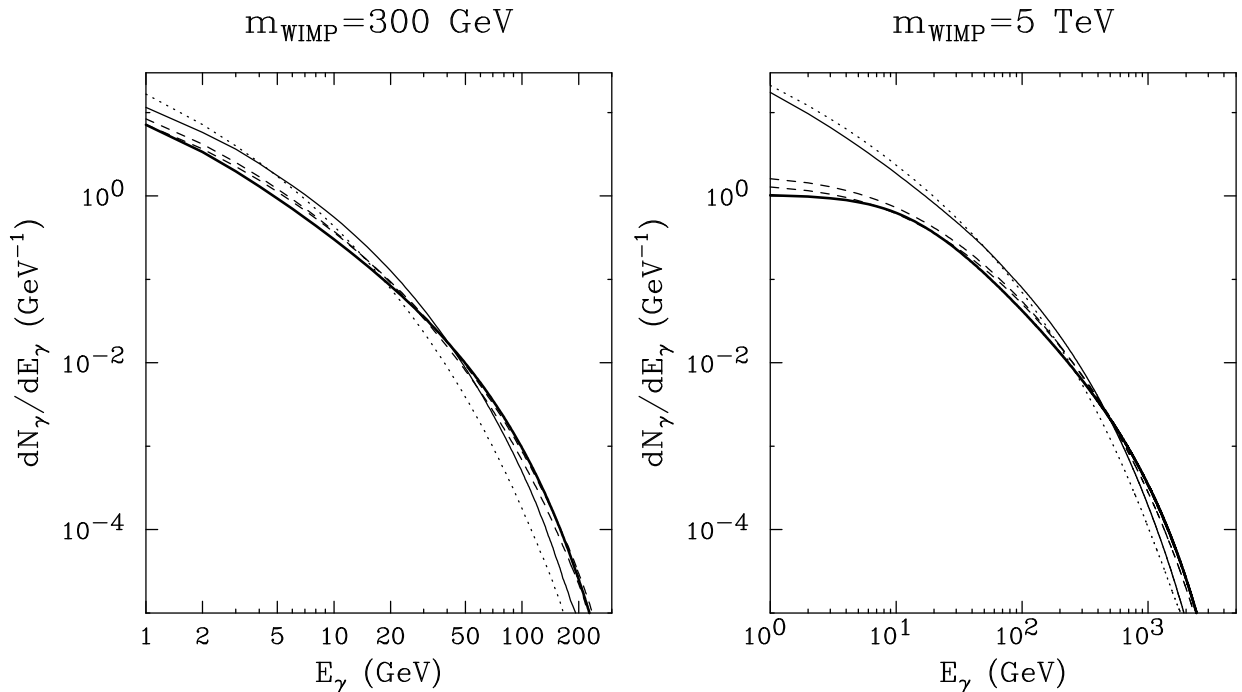
Figure 1: The spectrum of γ-rays for dark matter annihilation to selected modes — $b\bar{b}$ (thin full line), $t\bar{t}$ (dotted line), W^+W^-, ZZ (dashed line). The parameterization of Eq. 3 is also shown (thick full line).

with here. If annihilations into heavy quarks are important, the spectrum will be modified — annihilations to $b\bar{b}$ and $t\bar{t}$ will produce fewer γ-rays in the energy range $0.1M_X < E_\gamma < M_X$, but more γ-rays at lower energies.

Alternatively, the processes $XX \to \gamma\gamma$ and $XX \to \gamma Z$ produce γ-rays with energies M_X and $M_X(1 - M_Z^2/4M_X^2)$, respectively. The flux of these lines is determined by the appropriate cross-sections for each process, which vary from model to model. For the range of possible cross-sections for line emission in supersymmetric models, see Ref. [29]. The flux of these lines is typically much smaller than the corresponding continuum flux.

The CANGAROO-II experiment has published their spectrum in six energy bins. These results are shown in Fig. 2 in comparison to the spectrum predicted by Eq. 3. The data from CANGAROO-II appears to fit the spectrum reasonably well for a 1–3 TeV dark matter particle. For a heavier particle, the spectrum measured by CANGAROO-II is much softer than would be predicted for annihilating dark matter. This is also in conflict with the Whipple experiment which finds a substantial flux above 2.8 TeV.

Given the integrated flux above 2.8 TeV recorded by Whipple (Eq. 1), the corresponding flux expected for EGRET, CANGAROO-II or HESS can be estimated for a given dark matter particle mass using the parameterization of Eq. 3. As seen in Fig. 3, the integrated flux observed by CANGAROO-II (Eq. 2) is consistent with the Whipple measurement only for a very heavy
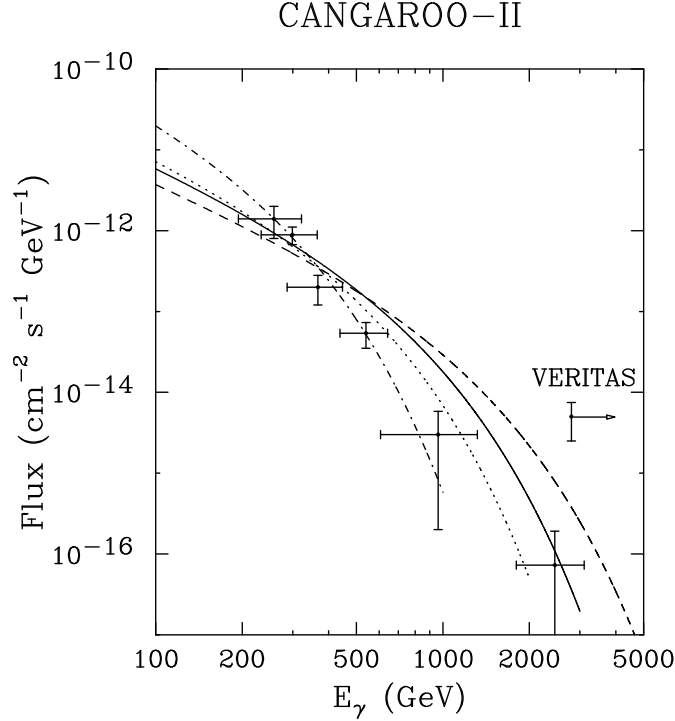
Figure 2: Data from the CANGAROO-II experiment compared with the spectrum predicted for dark matter annihilations to gauge bosons (see Eq. 3). The dot-dashed, dotted, solid and dashed lines are for 1, 2, 3 and 5 TeV particles. Normalization was considered a free parameter. Note that the highest energy bin shown (near 2.5 TeV) is less than 1 σ in excess of a null result, so should be taken only as an upper limit. Also shown is the flux measured by the VERITAS collaboration, inferred from the integral flux assuming the spectrum of a 5 TeV mass annihilating particle. Note the very different results of the two experiments.

particle (~ 10 TeV) which produces γ-rays primarily by continuum emission. This appears to be in contradiction with the results of Fig. 2. A somewhat lighter particle may be accomodated if the observed γ-rays have a significant component of line emission, however.

If dark matter annihilation indeed produces the TeV γ-rays observed by ACTs, then a lower energy component is expected to which EGRET (or in the future GLAST) is, in principle, sensitive. However EGRET has placed only an upper limit on the γ-ray flux from the Galactic center above 1 GeV [19]. This corresponds to an annihilation flux upper limit of $\sim 10^{-8} \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1}$ for a 100 GeV dark matter particle, and $\sim 10^{-7} \, \mathrm{cm}^{-2} \, \mathrm{s}^{-1}$ for a multi-TeV particle. Thus we see from Fig. 3 that a spectrum normalized to the Whipple observations will *violate* the EGRET bound if the particle mass is below about 3.5–4 TeV. If annihilations to modes other than gauge bosons dominate, this bound excludes masses up to about 5 TeV. On the other hand, if line emission is substantial, the corresponding flux in the range of EGRET's sensitivity would be reduced.
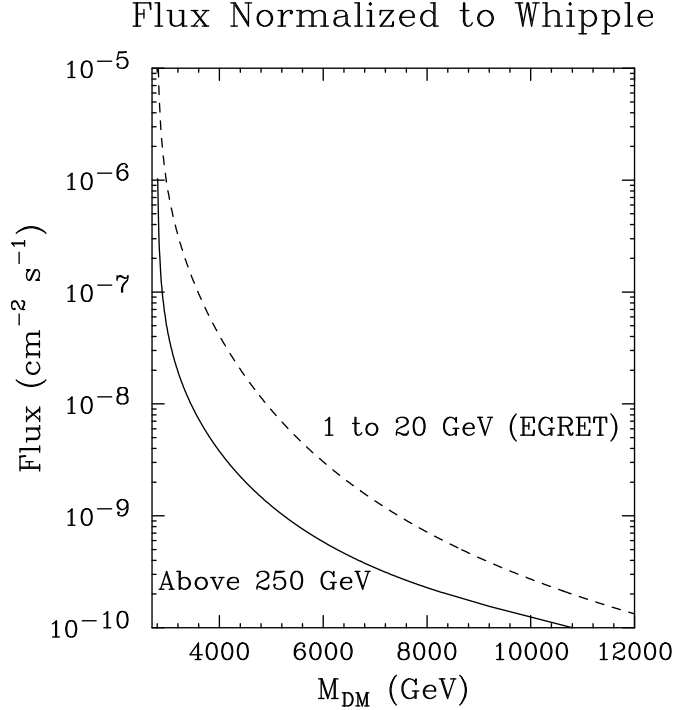
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Figure 3: The integrated flux predicted for CANGAROO-II, HESS (with 250 GeV thresholds) and EGRET if annihilating dark matter is the source of the γ-rays observed by Whipple. Annihilations primarily to gauge bosons are assumed (using the parameterization of Eq. 3). With CANGAROO-II's integrated flux of $\sim 2 \times 10^{-10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ above 250 GeV, only a very heavy dark matter particle (~ 10 TeV) is consistent with the CANGAROO-II and Whipple results, assuming continuum emission dominates. If line emission is significant, the mass may be somewhat smaller. If the particle mass is less than 3.5–4 TeV, the continuum emission from annihilations into gauge bosons exceeds the limit placed by EGRET [19], assuming a negligible line component. If dark matter annihilates mostly to another mode, such as heavy quark pairs, the EGRET limit may be violated for WIMPs as heavy as ~ 5 TeV.

4　The Annihilation Rate

The flux of γ-rays observed from the Galactic center, if interpreted as due to dark matter annihilation, can be used to constrain the annihilation cross-section of a dark matter candidate particle and the dark matter halo profile characteristics. The γ-ray flux from dark matter annihilations near the Galactic center is given by

$$\Phi_\gamma(\psi, E_\gamma) = \langle \sigma v \rangle \frac{dN_\gamma}{dE_\gamma} \frac{1}{4\pi M_X^2} \int_{\mathrm{los}} dl(\psi)\ \rho^2(r). \tag{4}$$

Here, ψ is the angle between the line-of-sight (los) and the Galactic center, $\langle \sigma v \rangle$ is the dark matter annihilation cross-section averaged over its velocity distribution, and $\rho(r)$ is the dark matter density at distance, r, from the Galactic center. This expression can be conveniently separated

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into two factors — the first specifying the particle physics model (mass, cross-section and fragmentation spectrum), and the second describing the dark matter distribution. Normalizing to the distance to the Galactic center and the local halo dark matter density, the latter factor can be written as:

$$J(\psi) = \frac{1}{8.5\,\text{kpc}} \left(\frac{1}{0.3\,\text{GeV/cm}^3} \right)^2 \int_{\text{los}} \text{dl}(\psi)\ \rho^2(\text{l}), \tag{5}$$

so we can calculate this factor for any assumed dark matter distribution near Galactic center. Then, defining $\overline{J(\Delta\Omega)}$ as the average of $J(\psi)$ over the solid angle $\Delta\Omega$ (centered on $\psi = 0$), we can write

$$\Phi_\gamma(\psi, E_\gamma) \simeq 5.6 \times 10^{-12}\ \text{cm}^{-2}\text{s}^{-1} \frac{\text{dN}_\gamma}{\text{dE}_\gamma} \left(\frac{\langle \sigma\text{v} \rangle}{3 \times 10^{-26}\text{cm}^3\text{s}^{-1}} \right) \left(\frac{\text{M}_\text{X}}{1\,\text{TeV}} \right)^{-2} \overline{J(\Delta\Omega)}\Delta\Omega. \tag{6}$$

For ACTs, which typically have angular resolutions of order $0.2°$, we will consider a solid angle of $\Delta\Omega \sim 5 \times 10^{-5}$ sr. The value of $\overline{J(\Delta\Omega)}$ can vary a great deal depending on the assumed dark matter distribution, e.g. for an NFW halo profile [42] $\overline{J(5 \times 10^{-5}\,\text{sr})} \simeq 5.6 \times 10^3$, while a Moore *et al.* halo profile [43] yields a considerably larger value, $\overline{J(5 \times 10^{-5}\,\text{sr})} \simeq 1.9 \times 10^6$.

It is possible, however, that these highly cusped profiles deduced from N-body simulations [44], do not accurately represent the distribution of dark matter in our halo. In particular, current N-body simulations cannot resolve halo profiles on scales smaller than roughly 1 kpc, and must rely on extrapolations in the innermost regions of the Galactic center [45]. Also, these simulations model halos without baryons, so may not be valid in the inner region of the Galaxy which is baryon dominated. If the baryons in the inner halo had been significantly heated in the past, they may have expanded outward, gravitationally pulling the dark matter and thus reducing its density in the innermost regions. Conversely, as baryonic matter loses energy through radiative processes, it will fall deeper into the Galaxy's gravitational well, pulling dark matter along with it; halo models which include this 'adiabatic compression' effect predict substantially higher dark matter densities near the Galactic center [46]. Alternatively, adiabatic accretion of dark matter onto the Super-Massive Black Hole (SMBH) at the center of our Galaxy occuring as a consequence of adiabatic growth of the SMBH may have produced a density 'spike' in the halo profile [47]. If this is the case, a very bright γ-ray source could be produced from dark matter annihilations. Such a spike could have been destroyed in a series of hierarchical mergers [48] although such mergers are unlikely to have occurred in the recent history of the Milky Way. The spike would most likely have been modified in the earliest stages of SMBH growth, however, when some mergers should have occurred. A more likely continual source of softening of the spike is the effect of stellar encounters [49]. However the annihilation flux is still enhanced in this case relative to the cusp in the absence of the SMBH. Moreover such a spike may provide the source of relativistic electrons needed to account for the low frequency radio emission from Sgr A* [50]. There is no merit in a recent claim that the density spike is inconsistent with radio observations of the Galactic Center, since this study only considered the case of an initial NFW profile; the processes described above will inevitably soften the profile [51]. It is even possible that other massive black holes are present in the Galactic center region, being failed mergers
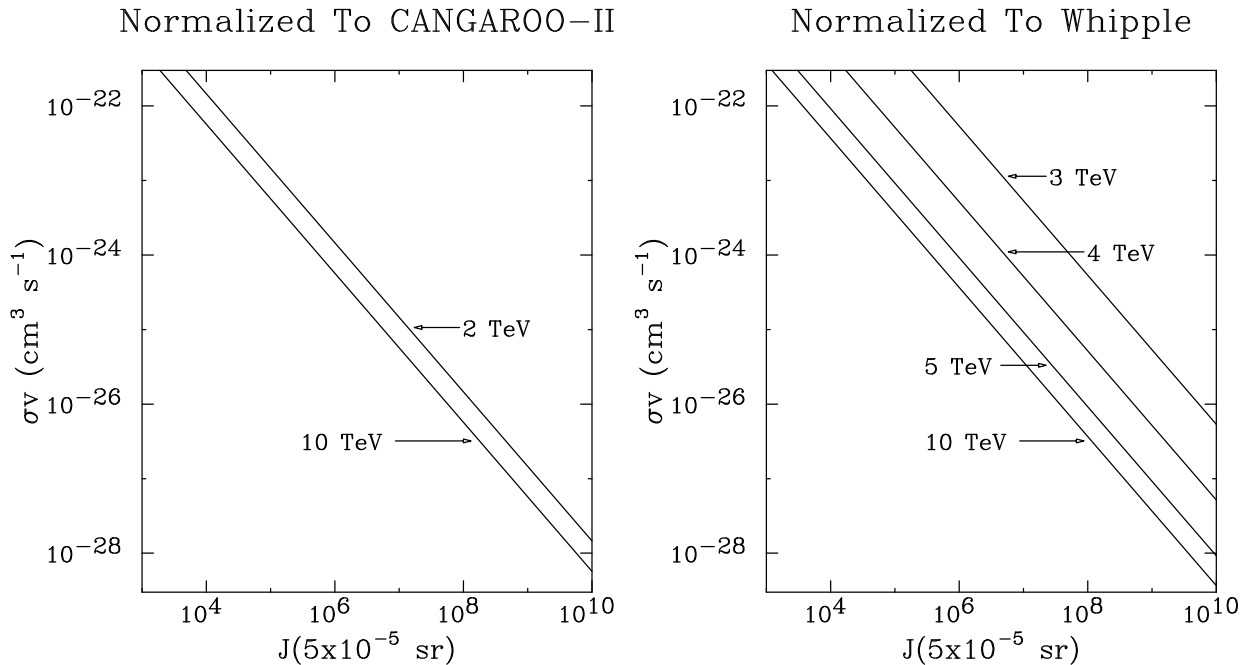
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Figure 4: The annihilation cross-section and halo profile needed to provide the γ-ray flux observed by CANGAROO-II (left) and Whipple (right). Contours are shown for several dark matter particle masses.

that are relics of the "final parsec" problem [52], as predicted by hierarchical merging scenarios that are normalised to the observed SMBH mass-spheroid velocity dispersion relation [53, 54]. These objects, which cumulatively contain as much mass as the central SMBH, would most likely have retained their CDM spikes generated if they formed adiabatically in the cores of pregalactic dwarf Galaxies, and hence are potential γ-ray sources.

There are other observations which can be used to constrain the dark matter distribution. In particular, by studying microlensing events in the direction of the Galactic Bulge, the quantity of dark matter within the Solar circle can be constrained. Binney and Evans [55] have argued that the observed number of microlensing events can be used to exclude cuspy halo profiles with inner power-law indices greater than about 0.3; for comparison, NFW and Moore *et al.* profiles have indices of 1.0 and 1.5, respectively. However, Klypin *et al.* claim to find reasonable agreement between observational data and cuspy halo profiles [56] and argue furthermore that there is no conflict with microlensing data if adibatic compression is included [46]. These authors also study the effects of angular momentum transfer from a fast rotating central bar which can help diminish the spike. We note that their different conclusion is in large part due to the adoption of a significantly lower microlensing optical depth towards the GC than considered by Binney and Evans. Given this wide range of opinions regarding the halo dark matter profile, it may be prudent not to exclude any of these models from our discussion.

We now turn our attention to the parameters set by the particle physics of the dark matter

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candidate, in particular the annihilation cross-section which also determines its relic thermal abundance. In the simplest situation, where the annihilation cross-section is *independent* of velocity, the relic abundance is approximately given by

$$\Omega_X h^2 \sim \left(\frac{\langle \sigma v \rangle}{3 \times 10^{-27} \, \text{cm}^3 \text{s}^{-1}} \right)^{-1}. \tag{7}$$

Of course, the annihilation cross-section is generally not velocity-independent. If it is larger at high velocities, the cross-section at low velocities will need to be smaller to yield the same relic abundance. Similarly, if resonances or co-annihilations significantly reduce the relic abundance, a smaller annihilation cross-section at low velocities will be required to match the measured density of dark matter. Although there are certainly exceptions to this estimate, it is reasonable to consider $3 \times 10^{-26} \, \text{cm}^3 \, \text{s}^{-1}$ (or ~ 10 pb) as an upper limit for the (low velocity) annihilation cross-section for a thermal relic which makes up the cold dark matter. Of course, this limit could be exceeded if the relic abundance did not result from an initial state of thermal equlibrium. A non-thermally produced dark matter particle could have a considerably larger annihilation cross-section.

In figure 4, we show the annihilation cross-sections and values of $\overline{J(5 \times 10^{-5} \, \text{sr})}$ needed to accomodate the CANGAROO-II (left) and Whipple (right) observations. For an NFW halo profile $(\overline{J(5 \times 10^{-5} \, \text{sr})} \sim 10^4)$, very large cross-sections of $\sim 10^{-23} \, \text{cm}^3 \, \text{s}^{-1}$ would be required to match the fluxes detected by Whipple or CANGAROO-II. A thermal relic with such a large cross-section would not yield a significant relic abundance. On the other hand, if we consider a more centrally concentrated halo distribution, such as a Moore *et al.* profile with adiabatic compression, $\overline{J(5 \times 10^{-5} \, \text{sr})}$ could be as large as $\sim 10^8$. In this case, cross-sections on the order of $\sim 3 \times 10^{-26} \, \text{cm}^3 \, \text{s}^{-1}$ could suffice to match the observed fluxes. Spiked density profiles could readily accommodate the observed flux. Indeed, one could even dispense with the need for the spike to surround the central SMBH, provided that another pregalactic VMBH which had retained its spike would be within a few parsecs of the GC.

5 The Dark Matter Distribution

The observations of the Galactic center made by Whipple and CANGAROO-II are consistent with emission from a point source. These experiments have angular resolutions of order 10 arcminutes, however, so the source may be extended roughly up to this angular scale. Each experiment's result is also consistent, to within their angular resolutions, with emission from the Galaxy's dynamical center. A skymap showing the regions corresponding to the CANGAROO-II and Whipple detections is shown in Fig. 5. In Fig. 6, a similar map is shown including X-ray and radio observations of the region.

The angular distribution of γ-rays from dark matter annihilations can be calculated for a given halo profile. At one extreme, profiles with a density spike predict an angular distribution which is essentially a point source with a negligible width. At the other extreme, a profile with
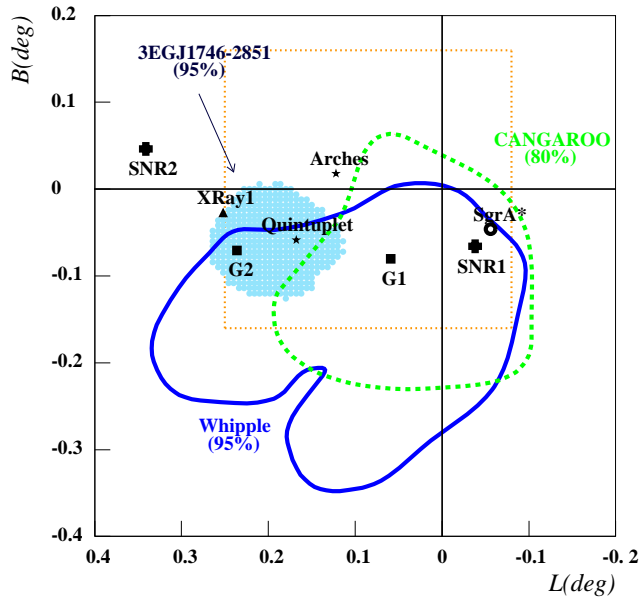
Figure 5: A skymap of the Galactic center region. The solid and dashed contours correspond to the regions observed by Whipple and CANGAROO-II, respectively. In these regions the observed significance is greater than 95% for Whipple and 80% for CANGAROO-II. The 95% confidence region for the off-center source observed by EGRET (3EG J1746-2851) is shown as a shaded region. Also shown are a number of selected objects known to be present in the region including Sgr A* (the dynamical center of the Galaxy and location of the supermassive black hole), two supernova remnants (SNR1 and SNR2, corresponding to Sgr A East and SNR 000.3+00.0, respectively), the Arches and Quintuplet star clusters, the low mass X-ray binary 1E 1743.1-2843 and two γ-ray sources observed by INTEGRAL (G1 and G2). The boxed area is the region shown in Fig. 6

a flat core in the inner few kiloparsecs will imply a rather extended distribution which cannot be reconciled with the recent observations by ACTs.

Cusped halo profiles fall between these extremes. In Fig. 7, we show the angular distribution of γ-rays predicted using an NFW halo profile for experiments with sub-arcminute, 10 arcminute and 20 arcminute resolution. It is clear that with present data, it is impossible to differentiate between an NFW halo profile and a point source. The same conclusion is reached if other cusped distributions or adiabatically compressed profiles are considered.

There is, of course, the possibility that the γ-rays observed by Whipple and CANGAROO-II are *not* from dark matter annihilations, but rather originate from some astrophysical source. In particular, there exists a source of 100 MeV to 15 GeV γ-rays which was observed by EGRET approximately $0.2°$ away from the Galactic center (see figure 5). Given their limited angular
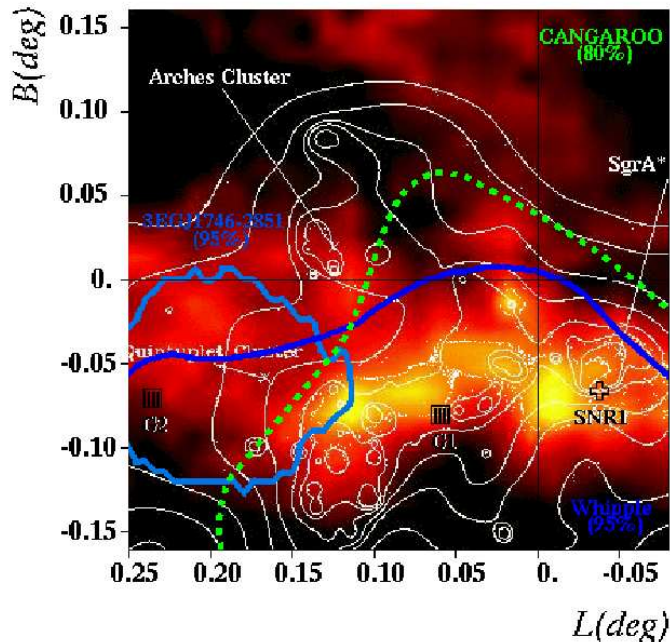
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Figure 6: A skymap of the Galactic center region overlaid with the results of the Chandra X-ray telescope at 6.4 keV (shading) and radio observations (thin contours) [57]. The objects, thick contours and regions shown are the same as in Fig. 5. The 95% confidence region observed by EGRET is shown as a solid contour in the lower left quadrant of the figure. The X-ray/radio map is provided courtesy of Q. D. Wang.

resolution, this location is *consistent* with the observations made by Whipple and CANGAROO-II. Future experiments with improved angular resolution will be needed to determine if the TeV emission from this region originates from the Galaxy's dynamical center, or from an offset direction. In particular, the HESS experiment has begun operating with four telescopes which should improve the angular resolution by a factor of 2 over a single telescope. GLAST will also have substantially better angular resolution than its predecessor EGRET.

6   Particle Dark Matter Candidates

For annihilating dark matter to accommodate the recent observations of ACTs, Whipple in particular, the dark matter candidate must be a few TeV or heavier. In models of softly broken
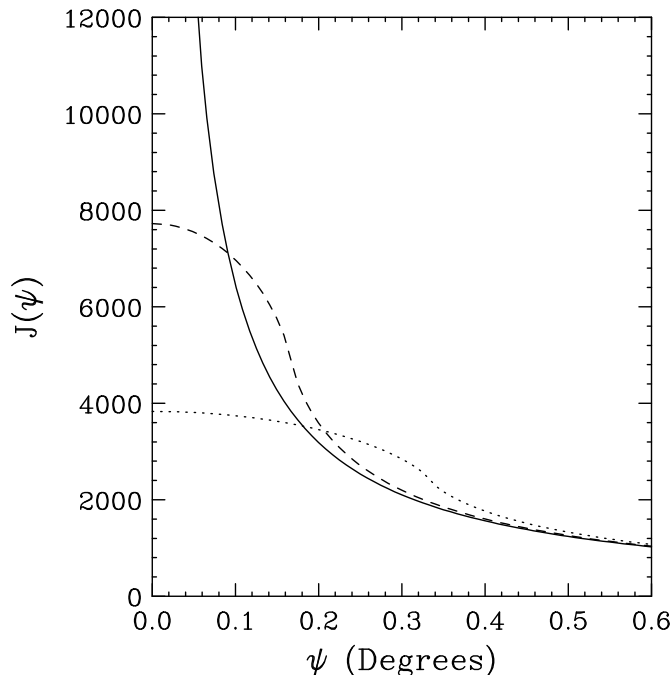
Figure 7: The angular distribution of γ-rays predicted from dark matter annihilations assuming an NFW halo profile, for an experiment with sub-arcminute (solid line), 10 arcminute (dashed line) and 20 arcminute (dotted line) angular resolution. Current ACT observations of the Galactic center cannot differentiate a cuspy halo profile from a point source.

supersymmetry, the lightest supersymmetric particle is not usually expected to be so heavy, being more natural near the electroweak scale. However, TeV-scale masses are not necessarily fine tuned, *e.g.*, in the focus point region of the constrained minimal supersymmetric standard model (sometimes called mSUGRA), neutralinos have such masses [58]. In such models, the lightest neutralino is typically a higgsino or a mixed gaugino-higgsino, and thus annihilates mostly to gauge boson pairs (rather than heavy quarks).

Outside of the focus point region, multi-TeV neutralinos can provide the observed dark matter relic density only in special scenarios. For example, if the CP-odd Higgs boson is very nearly twice the mass of the lightest neutralino, annihilations can occur at resonance, again allowing for TeV scale dark matter [59]. This situation can arise in the large $\tan\beta$ region of radiative gauge symmetry breaking models, such as mSUGRA. Alternatively, if the lightest neutralino is nearly degenerate with another supersymmetric particle (such as a stop or stau), coannihilations can deplete the thermal relic density, thus allowing for heavy neutralino dark matter [60]. It should be said that despite these possibilities, supersymmetry is typically expected to appear well below the TeV-scale.

The γ-ray signatures for supersymmetric dark matter have been studied extensively in the literature (see, for example, Refs. [28, 29, 30, 19, 41]). If a multi-TeV neutralino is indeed responsible for the observed γ-ray emission, supersymmetry will be very difficult to study in accelerator

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experiments, such as the Large Hadron Collider (LHC), making astro-particle experiments a more viable probe.

Thus far, we have only discussed dark matter which is a thermal relic. In neutralinos are produced in non-thermal processes well after the freeze-out epoch, the dark matter candidate may have a much larger annihilation cross-section than for the case of a thermal relic. For example, in anomaly-mediated supersymmetry breaking, the lightest neutralino is Wino-like with annihilation cross-sections larger than in most other supersymmetry scenarios. Such a dark matter candidate may require non-thermal mechanisms to generate the observed dark matter density [61].

In addition to supersymmetry, other extensions of the Standard Model can also provide a viable dark matter candidate. These include Kaluza-Klein dark matter in models with universal extra dimension [62], scalar dark matter in 'theory space little Higgs' models [63] and models with very heavy neutrinos [64]. Although there are numerous other examples of potentially interesting dark matter candidates discussed in the literature, it is beyond the scope of this paper to discuss them here.

7   Summary and Conclusions

In this article, we have discussed the possibility that annihilating dark matter in the Galactic center has produced the flux of γ-rays observed by the CANGAROO and VERITAS collaborations. Although it is possible that these γ-rays are the result of astrophysical processes, we summarize here the characteristics required of a dark matter particle, if its annihilations are responsible for the observed γ-ray emission.

7.1   The Spectrum

It is difficult to reconcile the spectra observed by the CANGAROO-II and Whipple experiments. The spectrum measured by CANGAROO-II is consistent with an annihilating particle of mass in the range of 1–3 TeV. On the other hand, Whipple has observed a substantial flux above its rather high threshold of 2.8 TeV, requiring a much heavier dark matter particle. Future observations will be needed to conclusively determine the spectrum of γ-rays from the Galactic center in the GeV-TeV range.

7.2   The Halo Profile and Annihilation Cross Section

For annihilating dark matter to produce the flux measured by either the CANGAROO or VERITAS collaborations, very high annihilation rates are required. This, in turn, requires a very large annihilation cross-section *and* a very concentrated dark matter distribution in the innermost region of our Galaxy. Even if we consider a particle with a rather large annihilation cross-section, say $\sim 10^{-26}$ cm^3/s, extremely cusped halo models, such as a Moore *et al.* with adiabatic compression would be required. Alternatively, halo profiles with a density spike most plausibly associated

with the central SMBH or a nearby VMBH could provide the observed flux.

7.3 Future Prospects

With the current data, it is very difficult to determine whether the γ-rays observed from the Galactic center region by CANGAROO-II and Whipple are the product of dark matter annihilations rather than other, less exotic, astrophysics. This state of affairs may change with improved data in the future. As the angular resolution of ACTs (as well as space-based γ-ray experiments, such as GLAST) improves, it will become clear whether the observed TeV emission comes from our Galaxy's dynamical center rather than from nearby star clusters, X-ray binaries or other objects. This information will be crucial for confidently identifying TeV emission as the product of dark matter annihilations.

Moreover, as the γ-ray spectrum in the GeV to multi-TeV range becomes more refined, it may become possible to ascertain whether the observed emission is the result of annihilating dark matter. In particular, evidence of line emission would provide a "smoking gun" signal for anihilations. Presently, we are eagerly awaiting results from the HESS collaboration, which has also been observing the Galactic center. HESS should be more sensitive in the direction of the Galactic center than either CANGAROO-II or Whipple. Also, with four telescopes, HESS's angular resolution should be superior to single-telescope ACTs.

Acknowledgments

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